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Sawing simulation of maritime pine (*Pinus pinaster* Ait.) stems for production of heartwood containing components

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Abstract

Natural durable heartwood products have less dimensional changes and are an environmentally friendly alternative to the use of preservatives. The present study explores the potential for the production of products containing heartwood from maritime pine (*Pinus pinaster* Ait.). The study was based on 30 virtual maritime pine stems that were mathematically reconstructed including description of external shape, internal knot architecture and heartwood. Stems were used as raw material input data for simulation of bucking and sawing. The impact of raw material characteristics and final products requirements on sawing yields was studied for production of components for glued laminated boards and for windows. Log and heartwood diameters were found to be the most influencing variables on final yields. The position of the log within the stem was also important while log length did not influence final yields (around 5% batch yield for all length groups). The highest sawing yields, 13% of heartwood products from log total volume, were found with 3 m logs bucked between 3 and 9 m height of 83 yr old trees. There is potential for the production of maritime pine heartwood products with additional efforts to be done in log and product sorting.

1 INTRODUCTION

Most tree species show two distinct zones in the xylem: the outer sapwood and the inner heartwood. The formation of heartwood results from the natural ageing of the tree, and varies with species, genetics and growth conditions. Reviews can be found at Taylor et al. (2002), Hillis (1987) and Bamber and Fukazawa (1985). Heartwood and sapwood have different color, density, moisture content, chemical composition, mechanical and technical properties such as natural durability and suitability for chemical treatments. The content of sapwood and heartwood has therefore a significant impact on the utilization of wood. In pulping, the heartwood extractives affect negatively the process and product properties. For solid wood applications the different properties of heartwood and sapwood influence several unit operations, i.e. drying, adhesion to glues and paints, and issues such as aesthetic values for the consumer and ecological concerns, since the natural durable heartwood products offer an environmentally friendly alternative to preservatives. When there is a large color difference between sapwood and heartwood, selection of wood components by color also plays a significant role in some timber applications.

Some heartwood products are already successfully commercialized (e.g. floors and windows) and industrial interest is growing. The possibility of applying techniques to reduce defects and material heterogeneity i.e. finger joint, increases their competitiveness in relation to substitute materials.

The number of studies on the potential of heartwood-targeted products is very limited. Toverød et al. (2003) simulated the sawing of Scots pine (*Pinus sylvestris* L.) trees in order to optimize sawing patterns in function of heartwood products yields.

Within the wood conversion chain, sawing simulation tools have been developed to optimise production, linking raw material properties to industrial production planning (Usenius 1999, Schmoldt et al. 1996, Todoroki 1996, Leban and Duchanois 1990, Hallock et al. 1978). The impact of specific conversion variables and scenarios on sawing yields was analysed using the virtual sawing of logs and trees (Ikonen et al. 2003, Pinto et al. 2002, Maness and Lin 1995, Todoroki 1994, Richards 1973). Simulation techniques may be applied to the heartwood component of stems, and this was done for maritime pine (*Pinus pinaster* Ait.), a species with a strong reddish-brown heartwood in contrast with the pale yellow sapwood (Pinto et al. 2004). Maritime pine is an important softwood species in Southern Europe, with 3 million ha in Portugal, Spain and France, directed to the pulp, board and saw milling industries.

The virtual representation of maritime pine stems including internal knottiness (Pinto et al. 2003) and heartwood (Pinto et al. 2004) has already been done using three-dimensional reconstruction algorithms (Usenius 1999, Song 1998) and applied for sawing yield simulation studies (Pinto et al. 2002). The heartwood represents 17% and 12-13% of stem volume, up to 50% of tree height, respectively in 83 and 42-55 year old trees.

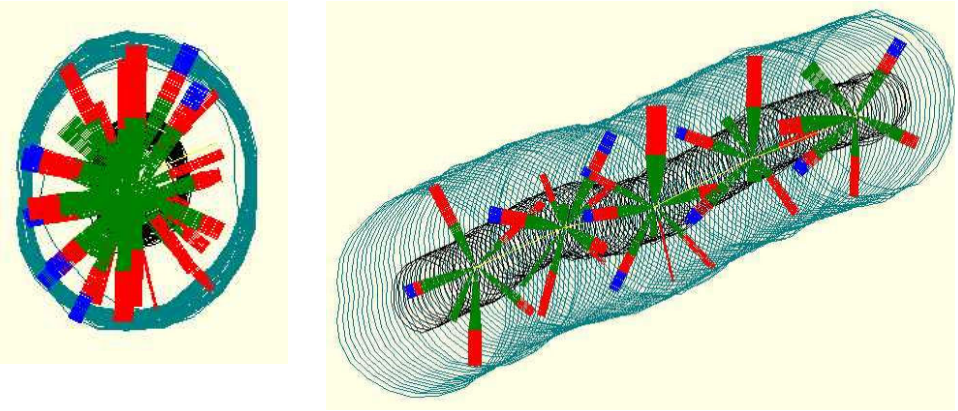
The objectives in the present study were to analyze the potential of Maritime pine stems for production of heartwood products, and to evaluate raw material and product variables that can influence it, by using sawing simulation tools for two product families: components for glued laminated boards and for window frames.

2. MATERIAL AND METHODS

Sawing yields in heartwood products were calculated using the bucking and sawing simulation modules of WoodCIM® after adaptation for maritime pine *(Pinus pinaster* Ait.) (Pinto et al. 2002). WoodCIM® is an integrated optimizing software system developed at VTT - Technical Research Centre of Finland (Usenius 1999, 2000) for the wood conversion chain. Virtual reconstructed stems were developed for maritime pine representing the external shape, internal knots and heartwood (Pinto et al. 2003, Pinto et al. 2004). The input data were supplied by the industry for two product families: components for glued laminated boards and windows.

2.1 Input data of raw material for sawing simulation

Thirty maritime pine trees were randomly sampled from three stands in Portugal: 20 from Leiria (LE), 5 from Alpiarça (AL) and 5 from Marco de Canaveses (MC). Data concerning site, stand and tree biometry were detailed in Pinto et al. 2004. In Leiria, the trees were 83 year old and had an average diameter at breast height (DBH) of 47.8 cm. In the other sites, trees aged between 42 and 55 years with average DBH of 38.9 and 42.7 cm. The heartwood volume contents (from 0 to 50% of tree height) were, in average, 15, 11 and 12%, respectively for LE, AL and MC sites. The trees were mathematically reconstructed into a set of virtual 3D stems using the so-called flitch method, where the data concerning the geometrical and quality features (i.e. heartwood and knots) were obtained by computing scanned images of flitches (Usenius 1999, Song 1987,1998). The virtual representation of the maritime pine stems has been described in Pinto et al. (2003, 2004). Figure 1 exemplifies the 3D and 2D representations for one maritime pine log showing external shape, internal knot architecture and heartwood.



a b

Figure 1: Representation of one maritime pine log showing in two (a) and three dimensions (b), the geometry of the log, the internal knot architecture and the heartwood part

2.2 Bucking and sawing simulation

The virtual reconstructed models of stems were used to predict the sawing yield using the bucking and sawing modules of the WoodCIM® software. Small adaptations were done to the program due to the larger stem diameters of maritime pine when compared to Scots pine and spruce, for which the bucking module was initially developed, i.e. screen stem size was re-scaled and the number of log lengths was increased from 7 to 10.

The sawing module can be applied using as input the virtual stem as well as only the heartwood part extracted from the stem, because heartwood was reconstructed with the same algorithms as used for the stem shape (Pinto et al. 2004). Therefore, heartwood can be virtually sawn separately from the stem thereby allowing the calculation of a sawing yield for heartwood products. By adapting different wane specifications it is possible to saw components with at least one heartwood face, the remaining volume being within the sapwood (Figure 2). The heartwood containing products are referred to as heartwood products.

The program calculated the sawing yield by using different sawing set-ups for each log and choosing the best combination of sawing pattern, dimensions and qualities of the sawn timber products. The nominal and green dimensions of sawn timber products, the quality requirements for each face, prices of sawn timber products and of by-products and saw kerfs were introduced as input variables. The simulation software module was also adapted for maritime pine (Pinto et al. 2002). The output gives the best set-up and sawing pattern, the number of sawn timber products by dimension and grade and the volume and value yield of sawn timber products. The results were obtained for the entire batch of logs, for individual logs and for a specified log group.

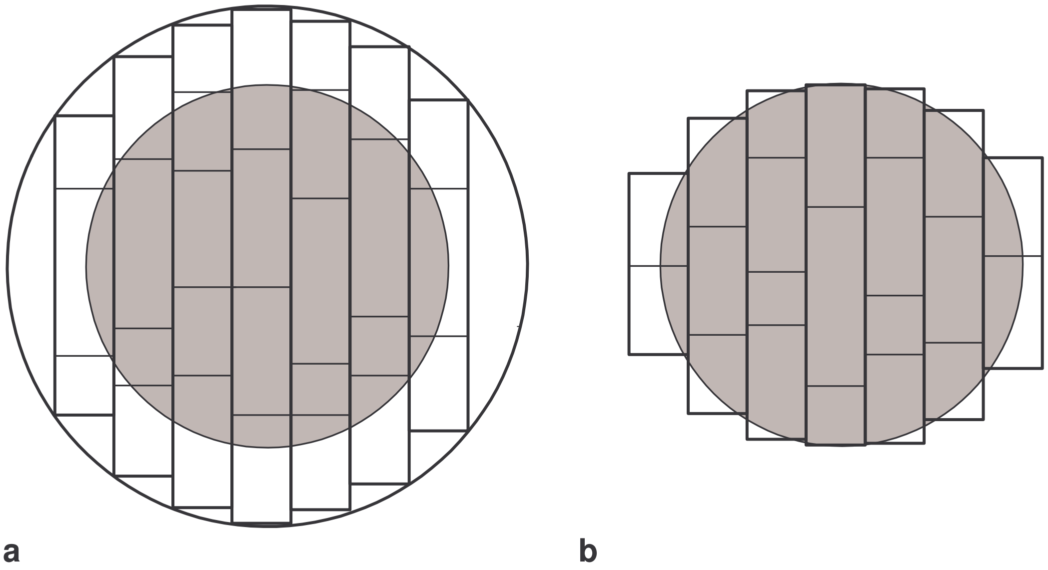


Figure 2: Schematic representation of the sawing simulation of whole log (a) and heartwood part (b)

2.3 Sawing set-ups and data analysis

2.3.1 Raw material and sawing process

The 30 virtual stems were bucked into four different log lengths: 2, 3, 4 and 5 m. The logs were grouped by top diameter into nine classes with 50 mm amplitude. The live sawing module was used to cut the logs into boards with the specified thickness and further to optimize the board cutting into the required components. The log was not allowed to rotate between simulations. The simulations were run for the log as well as for the heartwood. The yields obtained refer to total product yield from the log (Y), and to yield of heartwood products calculated in relation to log (Ylog) and heartwood (Yhtw) volumes. Table 1 describes the yield variables obtained with the sawing simulation and the log and heartwood characteristics.

2.3.2 End-product specifications

Two types of products were considered: components for glued laminated boards and components for windows. The dimensional and quality requirements of both components are given in Table 2. For heartwood components, wane was allowed in 95% of the thickness and in 100% of the width and length. Equal price was set for all products as the target in the present study was to obtain volume sawing yields.

All the logs were virtually sawn using the specifications for glued laminated boards and the results were analyzed in relation to the impact of raw material characteristics on the sawing yields. To study the influence of end-product requirements on sawing yields, simulations were run for the production of window components using a homogeneous sub-sample from stand LE of 30 logs, with 3 m length, and located between 3 and 9 m of stem height.

Table 1: Description and notation of yields and log (_log) and heartwood (_htw) variables

Variable	Notation	*Description*
Total Yield for log volume	***Y***	(Products volume/log volume) x 100(%)
Yield of heartwood products for log volume	***Ylog***	(Volume of Heartwood containing Products/log volume) x 100, (%)
Yield of heartwood products for heartwood volume	***Yhtw***	(Volume of Heartwood containing Products/heartwood volume) x 100 (%)
Top diameter	***DTlog,DThtw***	Average of 24 vectors that define the top cross-section (mm)
Butt diameter	***DBlog, DBhtw***	Average of 24 vectors that define the butt cross-section (mm)
Taper	***Tlog, Thtw***	Slope of the line marking the external limit of diameters determined every 50 mm of length (mm/m)
Pith curviness	***C***	Maximum deviation (in any direction) of pith, found along the log, in relation to an imaginary axis defined by a straight line connecting the pith points at butt and top end of the log (mm/m)
Position	***P***	Position in stem height of the log butt (m)

Table 2. Dimensions and quality requirements for the heartwood components specified in the sawing simulation

Components	***Dimensions (mm)***	***Quality***
Glued laminated boards	thickness: 18/25, 22/29 and 25/32 (final/green) width: 60 and 55 length: 950, 110, 1200, 1300, 1450, 1600, 1800, 2100, 2020, 2440	No restrictions on defects
Windows	thickness: 22/29 (final/green) width: 75, 100, 125 and 150 length: 400, 600, 800, 1000, 1200,1400,2000	Gade (*),*number of faces with knots allowed

3 RESULTS

3.1 Influence of raw material characteristics

The sawing of components for glued laminated boards was simulated for four bucking lengths. The results are summarized on Table 3 by log diameter classes. Regardless of log length about 65% of the bucked logs had a top diameter between 225 and 375 mm. Heartwood volume proportion within the log varied from 5 to 28%. Logs without enough heartwood volume to be sawn into the required components (0% yield) occurred in variable number for all diameter classes below 350 mm. For all length groups no log was sawn with top diameter below 125 mm and in diameter class of 150 mm only 20% of the sawn logs yielded heartwood products.

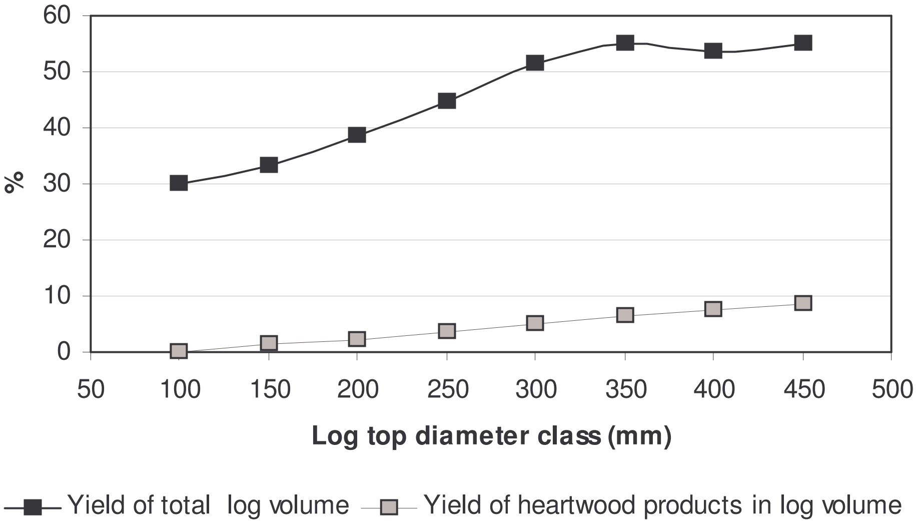


Figure 3. Sawing yields (of the total and of the heartwood volume) of components for glued laminated boards in % of log volume by log diameter class for 3 m long logs

Sawing yields increased with diameter for all log lengths, with the highest yields for classes 350 to 500 mm (Table 3). Figure 3 shows the sawing yields by log diameter class for 3 m long logs. Total yield of log sawing (Y) increased rapidly from around 30% for class 100 logs to 55% for class 350 logs, by adding approximately 5% yield per diameter class and kept rather constant in the following log classes. The yield of heartwood products (Ylog) also increased with the diameter class almost in a linear way. The difference between two neighboring classes was about 1%. The range of sawing yields of individual logs was large for all log diameter classes and lengths and several outliers were registered.

The influence of log and heartwood variables on the sawing yields was studied through correlation analysis (Table 4). Since heartwood content varies with tree age, the analysis was also carried out for the trees classified in two different age groups (80 and 42-55 years). Yield of heartwood products (Ylog) was highly correlated with heartwood variables (heartwood top diameter, proportion and volume) and with log top diameter. A negative correlation of log position in the stem with yield was also significant, though with lower correlation factors. Weak correlations were found with curviness and heartwood taper and none with log length and log taper.

Table 3: Simulation output for the sawing of heartwood components for glued laminated boards. Logs bucked to different lengths

Log length	**Diameter class**	**Number of logs**	**0 yield logs**	**Heartwood in log (%)**	**Yhtw**		**Ylog**	
m	mm (1)			min. - max.	%	sem(2)	%	sem(2)
2	100	2	2	5.0-9.4	0	0	0	0
	150	10	9	4.3-17.0	11.9	0	2.1	0
	200	42	35	3.0-22.4	15.9	3.2	2.3	0.6
	250	60	19	5.8-24.8	23.3	1.6	3.4	0.4
	300	61	9	2.9-27.9	29.9	1.2	5.0	0.3
	350	54	0	8.7-26.3	35.9	1.0	6.1	0.3
	400	30	0	8.4-26.8	39.7	1.3	6.8	0.5
	450	7	0	11.8-22.9	41.9	1.6	7.5	0.8
	500	4	0	15.8-24.3	45.6	1.5	8.7	0.5
3	100	1	1	7.3-15.5	0	0	0	0
	150	6	5	5.4-15.9	8.33	0	1.4	0
	200	24	19	4.1-21.3	14.3	5.7	2.1	0.5
	250	38	8	3.3-25.9	24.1	1.5	3.5	0.3
	300	41	2	4.2-27.7	30.8	1.4	5.0	0.4
	350	33	0	9.4-26.2	38.8	1.3	6.5	0.4
	400	18	0	8.4-26.6	42.2	1.8	7.4	0.6
	450	5	0	12.4-23.3	45.7	2.7	8.4	1.5
	500	2	0	16.1-19.8	48.9	2.6	8.7	0.4
4	100	2	2	5.5-13.9	0	0	0	0
	150	5	4	6.0-15.8	6.7	0	0.8	0
	200	22	14	3.5-17.0	12.5	1.9	1.6	0.3
	250	29	7	5.3-26.4	22.6	1.7	3.6	0.4
	300	31	2	3.5-27.4	30.4	1.5	4.8	0.5
	350	23	0	11.4-26.3	37.1	1.5	6.5	0.5
	400	12	0	8.7-25.5	40.4	2.4	6.8	0.4
	450	4	0	12.9-23.3	43.9	1.2	8.8	1.1
	500	1	0	16.8	51.2	0	8.6	0
5	100	0	0	0	0	0	0	0
	150	6	5	5.7-15.8	5.3	0	0.6	0
	200	14	6	3.7-17.7	10.6	1.9	1.4	0.3
	250	26	4	3.7-23.7	21.2	1.7	3.1	0.3
	300	22	1	4.2-28.6	27.4	1.8	4.2	0.5
	350	22	0	11.4-26.0	38.9	1.5	7.0	0.5
	400	8	0	9.3-25.7	40.4	3.5	7.1	1.2
	450	2	0	13.5-23.0	41.1	1.3	7.6	1.7
	500	1	0	17.3	50.8	0	8.8	0

(1) Central value of each class, amplitude is 50mm

(2) standard error of mean

Table 4. Results of correlation analysis of yield of heartwood products (Ylog) for glued laminated boards with several log and heartwood characteristics

	Total sample trees N=669	80 yr old trees N=475	42-55 yr old trees N=194
Heartwood top diameter	0.88**	0.87**	0.77**
Heartwood proportion	0.87**	0.92**	0.69**
Heartwood volume	0.75**	0.72**	0.70**
Log top diameter	0.73**	0.65**	0.68**
Log volume	0.54**	0.45**	0.51**
Log butt position in stem	-0.40**	-0.54**	-0.48*
Pith curviness	-0.21**	-0.13**	0.12
Heartwood taper	-0.19**	-0.25**	-0.12
Log taper	0.01	0.05	0.17*
Log length	0.01	0.01	-0.02

Pearson correlation, **correlation is significant at the 0,01 level (2-tailed),
*correlation is significant at the 0,05 level (2-tailed)

Influence of log length

The yield obtained by sawing heartwood components for glued laminated boards did not show significant differences with log length. Yields for all the logs (including 0% yield logs) were 4.8% and 5.4% of log volume respectively for 2 and 3 m logs, and 5.0% for 4 and 5 m logs. Impact of log length was higher for the lower log diameter class and for log diameters under 300 mm the yield clearly decreased with increasing log length.

Influence of log position

Figure 4 shows the distribution of Ylog with log position within the stem. In order to increase sample homogeneity only 3 m logs from LE trees were analyzed. The second and third log positions, i.e., logs in the stem zone between 3 to 9 m of height, showed the highest batch yields of heartwood components, 7 and 8% in log volume, respectively. The yield obtained with butt logs was similar (6% batch yield) but after 9 m height yield decreased rapidly to 2% for the log starting at 15 m height. These results followed closely the vertical distribution of heartwood volume proportion, i.e. higher heartwood volume content was found in the second and third logs representing 18% of the log volume.

Influence of log diameter

The yield of heartwood components increased with heartwood top diameter following a linear distribution (R^2= 77%), as shown on Figure 5a. Only logs with heartwood diameters over 100 mm could yield heartwood components in the sawing. The only exceptions were two logs with high curviness and very irregular heartwood shape, therefore considered as outliers and excluded from the analysis. The variability of yields was always large especially for heartwood diameters in the range of 100-175 mm,(Table 3). For logs with heartwood diameters over 175 mm batch yield was 8% and the variability of results was low (stdev 2.3%). Below a heartwood diameter of 100 mm, 52% of the logs had 0% yield while for the remaining logs the yield varied from 0.5 to 6%.

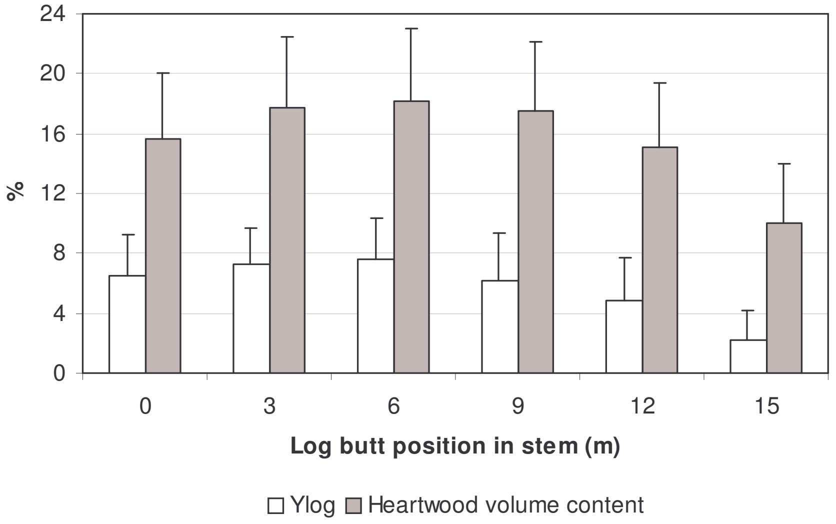


Figure 4. Yield of heartwood components (Ylog) for glued laminated boards and heartwood volume content, for logs in different positions along the stem. (Mean of 20 logs; error bars are sdev)

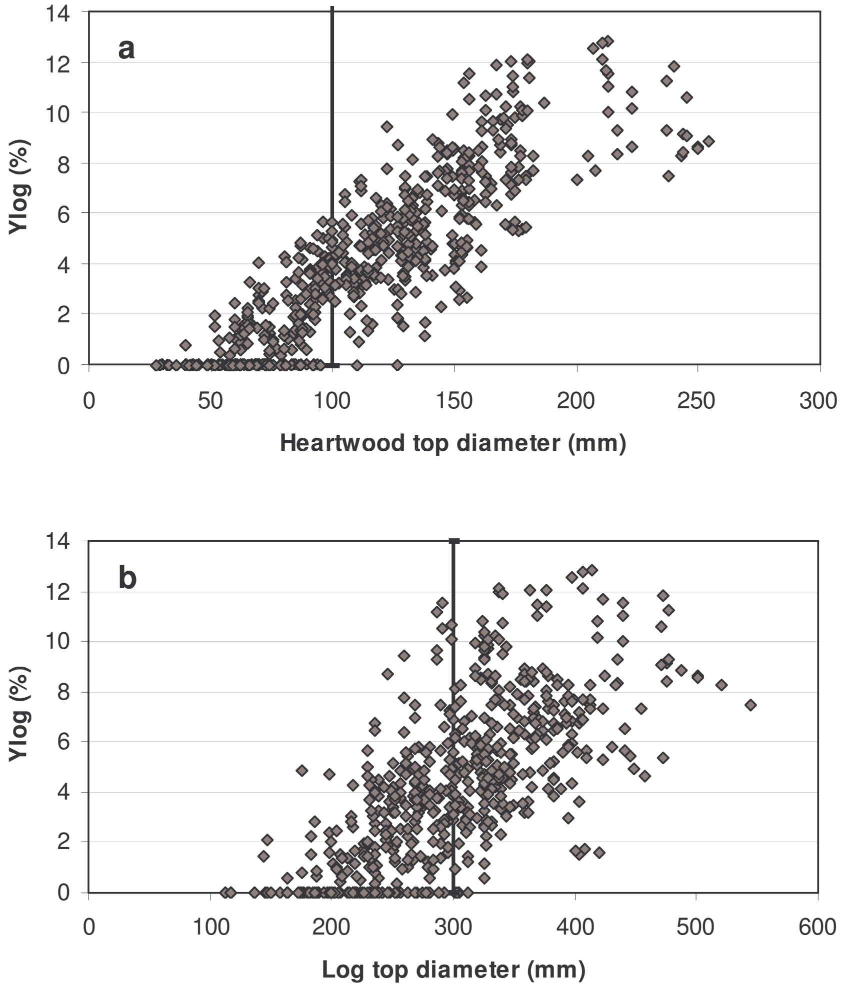


Figure 5: Yield of heartwood products for glued laminated boards as a function of heartwood top diameter (a, R^2=77%) and log top diameter (b, R^2=53%)

The yield obtained in function of log top diameter (Figure 5b) also showed an increasing trend but the variability was high. With log top diameters over 400 mm, the average yield of heartwood products was 8% (sdev 2.8%). Logs with top diameters over 300 mm allowed always production of heartwood components, while for 31% of the logs with top diameters between 200 and 300 mm the yield was 0%. However, even in this diameter range it was possible to obtain heartwood products with yields between 5 and 12% for 14% of the logs.

3.2. Prediction of sawing yields for heartwood products

Prediction of sawing yields in heartwood products was made through the fitting of models using log and heartwood variables. The best models are summarized in Table 5. Log top diameter allowed to predict 53% of the variation while addition of other log variables such as taper or curviness did not improve very much the prediction. Better predictions were obtained using the heartwood diameter as a variable (77% of the variation) and from addition of other variables did not result any improvement.

Table 5: Models to predict sawing yields of heartwood products for glued laminated boards in relation to log volume using log and heartwood variables

	Adjusted r2 (%)	**Standard error of estimation**	**Selected models**
1	53.0	2.24	$Ylog = 0.032\ Dlog - 5.4$
2	57.0	2.15	$Ylog = 0.031\ Dlog - 0.1\ Tlog - 0.1\ P - 3.1$
3	76.7	1.58	$Ylog = 0.063\ Dhtw - 3.1$
4	76.8	1.58	$Ylog = 0.068\ Dhtw - 0.004\ Dlog - 2.6$
5	76.9	1.57	$Ylog = 0.065\ Dhtw + 0.039\ P - 3.17$

3.3. Influence of product requirements

The impact of product requirements in heartwood sawing was studied for component products for windows. Raw-material was a sample of 30 logs with 3 m length (bucked between 3 to 9 m stem height) and top diameter between 268 and 476 mm. The yields obtained by the sawing of the total log volume and the yields of heartwood products with different quality specifications regarding the number of faces with knots, are summarized in Table 6. The batch yield with no restrictions on component quality (i.e. knots allowed in all faces) was 62% while the yield in heartwood products was 10% of the log volume.

The impact of increasing quality demand was higher in heartwood products (Ylog) than in total products (Y) (Table 6). For the log, yield increased about 8.8% from grade (0) to (4) while for the heartwood volume it increased only by 3.5%. The largest differences were obtained when the set-up conditions changed from no restrictions on quality [grade (4)] to restrictions in only one face [grade (3)], resulting into yield increases of 3% and 7% for Yhtw and Y, respectively.

Table 6: Total yield (Y) and yield in heartwood products (Ylog) in relation to log volume obtained for window components with different quality grades regarding the number of faces with knots

Grade	Y	Ylog
0	53.6	6.9
1	53.7	6.9
2	54.0	7.0
3	55.8	7.4
4	62.3	10.4

The distribution of heartwood components by length and width is shown in Fig. 6 for grades 0 and 4. The quality requirements had a major impact on the distribution of the sawn components dimensions. When no restrictions in quality were made, 40% of the sawing components had 3000 mm length and 17% had 400 mm length. There was a clear reduction on component dimensions when no knots were allowed in any component face. For this set-up 82% of the sawing components had 400 and 600 mm lengths while only 2.4 % had 2000 and 3000 mm lengths.

4 DISCUSSION

The mathematical reconstructed stems, including the internal knot architecture and the heartwood (Figure 1), provided a good tool for the virtual bucking and sawing simulations. The 3D reconstruction of maritime pine heartwood had been previously tested and showed a good accuracy (Pinto et al, 2004). The results obtained when sawing the total log volume (Y) (Figure 3), also agree with a previous sawing simulation study for this species (Pinto et al, 2002).

The WoodCIM® software was not designed to include heartwood as an input parameter or as quality feature in the output (Usenius 1999, 2000). Therefore, the heartwood was taken in the input as an individual entity, separated from the log, a sort of “heartwood log” (Pinto et al. 2003). The full utilization of the heartwood was possible by allowing wane in the products (Figure 2).

This sawing procedure is a virtual concept and in a real industrial situation, the process would be to saw the whole log and subsequently use the heartwood content of sawn products as grading criteria. This means that sapwood products would also be obtained and these have to be taken into account for an overall economic analysis. However the differences between simulation and industrial reality should not affect the analysis of the impact of the different variables in the sawing yield of heartwood products, which was the objective of this study.

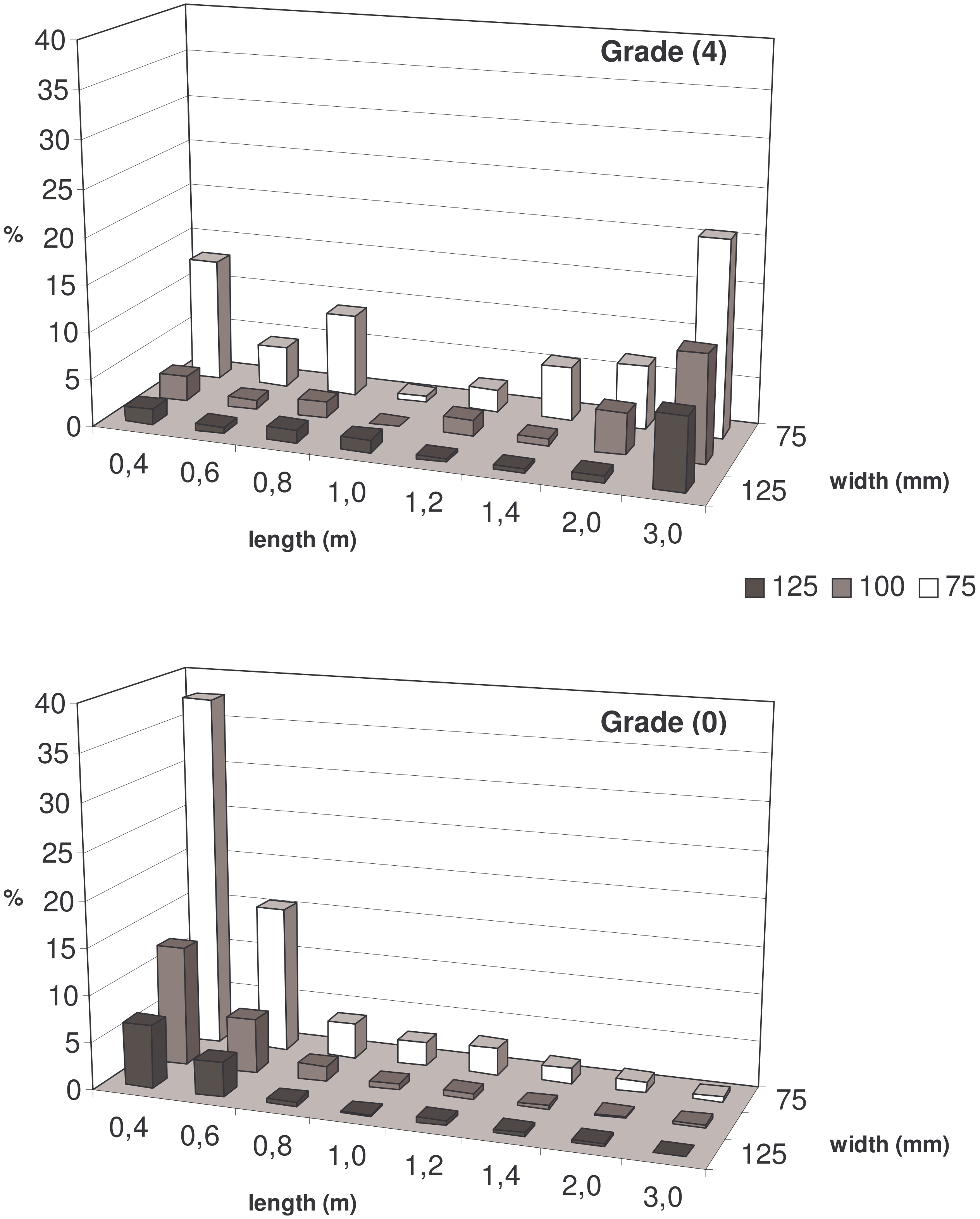


Figure 6: Frequency of dimensions of heartwood components (length and width) for sawing without any quality restrictions, concerning knots [grade (4)] and in the case knots were not allowed in the component's faces [grade (0)]

Windows and glued laminated boards were chosen as products due to the potential of increasing benefits and market share in case their production would be based on heartwood components. Glued laminated boards have a wide end-use application, *i.e.* doors, floors and panels, in which enhanced durability, dimensional stability and aesthetic value for the consumer can add value to the product. Windows are exposed to outside environment and higher durability and stability are needed to recover the market lost in recent years to PVC windows (Eastin et al, 2001).

Depending on end-use, some products might need the whole component volume to be of heartwood while others only require the visible face of heartwood. In this study the latter hypothesis was considered, thereby maximizing the sawing yields within the heartwood volume (Figure 2).

Regarding heartwood development in maritime pine stems, previous studies by Pinto et al (2004) have shown that it increases with age and in the older trees represents 17% of the stem volume (in 50% of the tree height). In general heartwood is regular and follows the growth ring outline. These features indicate a potential for the production of heartwood containing products.

The results obtained showed that log yields of heartwood products could attain 13% and 16% of log volume respectively for glued laminated boards and window components. The yield was highly variable with the log variables such as dimensions, original position in the stem and age, as well as with heartwood variables (Table 4). Therefore, yield for individual logs had a large spread, even when classified by diameter. For the higher diameter classes (>350 mm) batch yield of heartwood products were 7-8% of the log volume (Table 3). For the sawing simulation for glued laminated components, yield of heartwood products above 10% of log volume only occurred for logs for the LE stand, corresponding to the older trees. This stresses the importance of including a special selection of raw material within the log quality grading when the target is the production of heartwood products.

The variables that mostly impacted the sawing yield were log and heartwood top diameters and log position in the tree (Table 4). The highest yields were obtained when sawing 3 m logs, with top diameter above 375 mm and from the first 9 m of the stem of the older trees (83 years-old, LE stand).

The influence of log length (2 to 5 m) in yield was very small when sawing components without knot quality restrictions. This is in relation with the fact that a large number of component lengths was allowed, thereby obtaining a product with mixed lengths. Richards (1973) also reported a low impact of log taper and length on simulated sawing yields, when compared with the impact of other variables such as log diameter, sawing kerf, board thickness and edging method. The slightly better yields obtained for the 3 m logs (Table 3) probably results from the fact that these logs fit better the vertical heartwood profiles found for this species. The heartwood diameter proportion was maximum between 4-9 m of stem height; for the older trees, the maximum heartwood proportion (42% of stem diameter) was found, on average, at 8.8 m of stem height (Pinto et al. 2004). The heartwood volume proportion in the log showed the highest correlation with the sawing yield (Table 4). In fact, the second and third logs (3-6 and 6-9 m, respectively) showed the highest yields (around 8%) in accordance with their highest heartwood content (18%) (Figure 4).

Since heartwood and log diameters were the most influent variables on yield of heartwood products (Ylog) it is of interest to define a minimum diameter under which it is not possible to saw heartwood components (0% yield) or the yields are low. For the studied sample, these values were around 300 mm of log top diameter and 100 mm of heartwood top diameter (Figure 5). Stem diameter and heartwood diameter have been related through a quadratic function (Pinto et al, 2004), and for a stem diameter of 300 mm the corresponding heartwood diameter is 110 mm, in accordance with the results found here. However, the variability of the results was high, mainly for Ylog in function of log diameter. In a range of 100 mm of log top diameter (from 350 to 450 mm) Ylog can change from 1.5% to 13%.

The selection of logs for production of heartwood components should not be done only in respect of log diameter, even if this was the log variable with the highest influence (Table 4). The heartwood diameter was also an important variable and since in maritime pine heartwood tapers fast, the position of the log in the stem (e.g. being a butt or a top log) is very significant. Log selection for heartwood products will produce the highest potential yields when all the above variables are considered. A good log grading targeting the sawing optimization of these products will therefore be achieved through an efficient traceability system and by adapting machine vision systems for detection of heartwood, *i.e.* x-ray (Oja et al. 2001, Grundberg 1999).

However, it is also possible to adapt traditional grading systems to the selection of potential good heartwood logs through the measurement of log and/or heartwood diameters. Log diameters can be measured with the existing shape scanners and heartwood diameter with systems such as infra-red scanning (Gjerdrum, 2002). In this study it was possible to fit equations to predict sawing yields (Ylog) in function of log and/or heartwood diameter (Table 5). though, at this stage, these are limited to the sampled trees.

Toverød et al. (2003) simulated the sawing of Scots pines, aged between 121 and 231 years, in logs with 60-70% of heartwood volume. They obtained yields around 20% of log volume and the best yields were achieved using logs with diameter above 250 mm. Log diameter was found as the most important variable for yield variation. They reported that optimizing the sawing for production of heartwood products could increase the final profit even if the volume yield decreases.

As regards the influence of product dimensions, better yields were achieved with smaller dimensions since these fit better the reduced heartwood volume when compared with the log volume. However it is the change on quality requirements, regarding the presence of knots, that mostly impacts on yield (Table 6) and product dimensional assortment (Figure 6). The yield (Ylog) is drastically reduced with the increase of the number of defect-free faces in the component, especially when changing from grade (4) to (3) (decrease of 3% in batch yield). It is possible to produce defect-free components though, in this case, 38% of the components had the smallest allowed width and length (75 and 400 mm, respectively, Figure 6).

These results are the consequence of the internal knot architecture in maritime pine trees. A previous study on the knot content in the older trees (LE stand), indicated that the knot core varied from 28% of tree diameter at the stem bottom to 84% of tree diameter at 70% of total tree height (Pinto et al., 2003). For the same trees, the proportion of heartwood varied from 34% of the stem diameter at the bottom, to 24% at the top. This means that most of the heartwood volume is included in the knot core volume and the production of knot-free components is then mainly dependent on the inter-whorl length.

In conclusion, it was possible to identify the variables that mostly impact sawing yield for the production of heartwood components (DTlog, DThtw and P). For the sample studied here only the largest logs from older trees achieved highest yields. Therefore the production of heartwood products from maritime pine stems is possible with an efficient log grading system and additional efforts for selection of heartwood pieces after the conversion. However, the general low yields of heartwood products (Ylog) indicate that this production should carefully integrate the remaining products. Further work on sawing simulations and log sorting optimization programs will take into account the heartwood content of the pieces as an extra grading criterion.

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